# CHAPTER 1

# HISTORY OF THE DEVELOPMENT OF AIR CLEANING TECHNOLOGY IN THE NUCLEAR INDUSTRY

## 1.1 BRIEF HISTORY OF NUCLEAR AEROSOL FILTRATION

### 1.1.1 EARLY HIGH-EFFICIENCY FILTER PAPER DEVELOPMENT FOR MILITARY GAS MASK USE

In the early days of World War II, the British sent some filter paper extracted from captured German gas mask canisters to the U.S. Army Chemical Warfare Service Laboratories (CWS) at Edgewood, Maryland.[74] This German filter paper, which was made of fine asbestos dispersed in esparto grass, had unusually high particle retention characteristics, acceptable resistance to airflow, good dust storage, and resistance to plugging from oil-type screening smokes (a deficiency of the resin-wool filters then used by the British forces). The U.S. Army CWS, together with the U.S. Naval Research Laboratory (NRL), reproduced the German-designed filter paper and had it manufactured in large quantities on conventional papermaking machinery by the Hollingsworth and Vose Company in Massachusetts. The first successful paper produced for the U.S. Navy contained Bolivian crocidolite and was called H-60. The U.S. Army paper also contained Bolivian crocidolite and was first designated H-64, but was later called CWS Type 6. It was formulated from northern spruce sulfite and sulfate pulp (76 percent), cotton waste (15 percent), and Bolivian blue crocidolite asbestos (14 percent). Penetration was 0.025-0.04 percent based on a methylene blue stain-intensity test procedure.[19]

The National Defense Research Council (NDRC), acting for the armed services, solicited the assistance of a number of university and industrial scientists in the search for better smoke filters. This resulted in important U.S. advances in the theory and technology of aerosol filtration. Up to this time, aerosol filtration theory had been derived almost exclusively as an offshoot of water filtration knowledge. To meet then-current military requirements, however, researchers such as Nobel Laureate Irving Langmuir examined the physical basis for particle retention on fibers or small granules. Langmuir concluded that the principal mechanisms involved were (1) interception, which affected suspended particles of sizes substantially greater than 1.0 μm in diameter when moving through a devious flow path in a bed of porous material, and (2) diffusion, which affected suspended particles with diameters substantially smaller than 1.0 μm.[22] His analysis, later modified by Ramskill and Anderson to include inertia,[25] indicated that the combined effects of these forces on a particle would be at a minimum when the particle was 0.3 μm in diameter. Langmuir advised testing gas mask filters with smoke of this size to determine minimum retention efficiency and indicated that, when particles with diameters greater or smaller than 0.3 μm were present during field use of the gas mask, they would be removed at higher efficiency than the test particles.

After the war, Victor LaMer[20] of Columbia University performed many experiments to further examine Langmuir's theory of a minimum filterable particle size and concluded that efficiency declined as particle size decreased below 0.3 μm.[22] Other researchers' results confirmed a minimum filterable particle size, but not necessarily a diameter of 0.3 μm. This is understandable, as subsequent studies showed that forces not taken into account by Langmuir,[22] such as particle inertia, flow rate, and naturally occurring electrostatic charges on particles and filter medium, may also affect collection efficiency. Whatever the historical judgment may be concerning the correctness of Langmuir's theory, it affected U.S. filter technology profoundly and directly led to LaMer and Sinclair's development of the filter test used by the NDRC during 1942 through 1945. This filter test became the standard U.S. method for rating ultra-high-efficiency (i.e., absolute) filters.[20] Before, the U.S. Army Chemical Corps had been using a test aerosol generated from methylene blue dye (dispersed from water solution and dried) that was developed in 1940 by Walton.[31] Walton also developed a sodium flame test in 1941 to speed-up testing of gas mask canisters because of the relative slowness of the methylene blue test procedure.[31] The sodium flame test became the basis for the British standard test for high-efficiency filters.[7, 72]

### 1.1.2 DEVELOPMENT OF THE HEPA FILTER

Protection against chemical warfare agents is required for operational headquarters where, however, the wearing of an individual gas mask is impractical. For these situations, the U.S. Army Chemical Corps developed a mechanical blower and air purifier known as a "collective protector" unit. As relatively large air volume flow rates are required for effective use, the gas mask canister smoke filter, which uses CWS Type 6 filter paper, was fabricated into deep pleats separated by a spacer panel and sealed into a rigid rectangular frame using rubber cement. The spaces between the teeth of the comb-shaped separators provided air passages to the depths of the pleats and were inserted front and backs in alternate folds to direct contaminated air in and clean air out. The collector protector units were designed for use at the particulate removal stage by a combined chemical, biological, and radiological purification unit of the U.S. armed services. This development was highly fortunate, as later activities associated with the Manhattan Project created potential air pollution problems that could be solved only by using air filters with characteristics similar to those of the CWS filter. The U.S. Army Chemical Corps became the sole supplier of high-performance filters to the Manhattan Project, and later to the U.S. Atomic Energy Commission (AEC). In the late 1940s, the AEC adopted this type of filter for use in containment of airborne radioactive particles in the exhaust ventilation systems of experimental reactors, as well as for most other areas of nuclear research. In this application they were known as AEC filters or simply nuclear filters.

In recognition of their unusually high retention efficiency for very small particles, the U.S. Army Chemical Corps' collective protector filters were variously known as absolute, super-interception, and super-efficiency filters. The most widely used name, however, was high-efficiency particulate air (HEPA) filters, an acronym coined by Humphrey Gilbert, a Manhattan Project safety engineer, from the title of a 1961 publication called *High-Efficiency Particulate Air Filter Units*.[51] A HEPA filter was defined as a throwaway, extended-medium, dry-type filter with (1) a minimum particle removal efficiency of 99.95 percent (later raised to 99.97 percent) for a 0.3-μm monodisperse particle cloud; (2) a maximum resistance, when clean, of 25 mmwg when operated at rated airflow capacity, and (3) a rigid frame extending the full depth of the medium (**FIGURE 1.1**). HEPA filters have proven to be extraordinarily effective, reliable, and economical devices for removing radioactive and nonradioactive submicrometer-sized particles at a high rate of collection efficiency.

### 1.1.3 EARLY NUCLEAR FILTER DEVELOPMENTS IN THE UNITED STATES

The U.S. Government was disturbed by the fact that components of the filter medium used in the CWS filters [Bolivian or African crocidolite (Blue Bolivian asbestos) and African esparto grass] had to be imported and could be difficult to obtain. After a variety of domestic cellulose fibers (yucca, Kraft, and viscose) had been used successfully by the NRL and Hollingsworth and Vose Company as a replacement for esparto in trial runs, the AEC contracted the A.D. Little Company to develop a paper of equal or better filtration performance characteristics that could be manufactured entirely from fibers obtainable on the North American continent. Their investigations led them in the direction of coarse glass fibers as a substitute for cellulose, Canadian asbestos as a substitute for Bolivian blue, and resin-stiffened, corrugated Kraft paper separators as a substitute for the comb-like separators used in the CWS filter that had proved to be a significant obstruction to

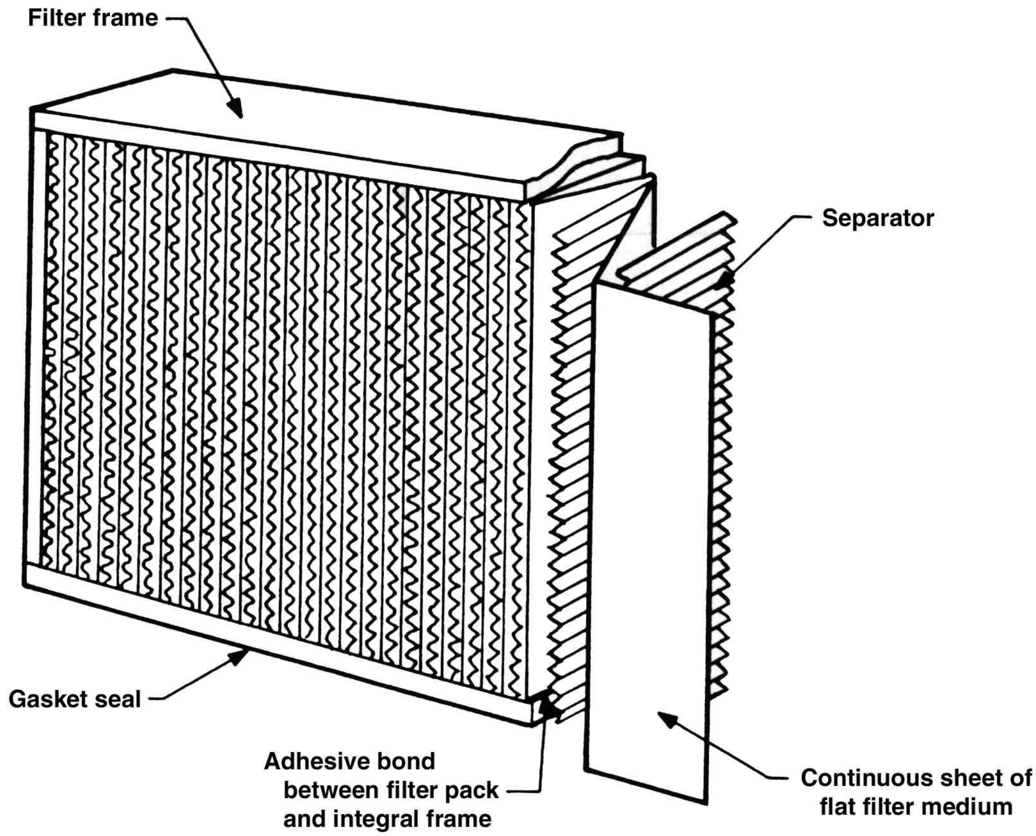


Figure 1.1 – HEPA filter design.

airflow.[27] The search for domestic sources of filter materials came to a highly successful conclusion in 1951 with the development (partly sponsored by the NRL) of an all-glass-fiber paper made partly from super-fine glass fibers with diameters substantially less than 1.0 μm.[24] As the domestic industry was able to produce unlimited quantities of glass fibers as small as 0.25 μm, asbestos was no longer needed. Abandonment of asbestos, which is difficult to disperse, allowed much greater control of manufacturing procedures and production of better and more uniform papers.

Because inclusion of some asbestos fibers in glass-fiber-containing absolute filter papers increases resistance to hydrogen fluoride and results in a slight cost reduction, some use of asbestos continued for a number of years even after it was known that the papers could be made without asbestos. International concern about the toxic properties of inhaled asbestos fibers ultimately resulted in total abandonment of the commercial use of asbestos-containing filter papers, as well as the use of corrugated asbestos paper for separators. Other materials were found that provided both improved resistance to chemical attack and fire resistance. Fires at the AEC's Rocky Flats Plant and in the Windscale graphite-moderated, air-cooled reactor in 1957 showed that noncombustible effluent filters were needed. The ability to make all-glass-fiber paper was a step in the right direction, but the separators, frame, and rubber cement used to seal the filter packs into the frames were all combustible. To overcome this problem, the A.D. Little Company was asked to develop a noncombustible absolute filter. They designed a prototype filter constructed from the glass-fiber filter paper prepared by NRL, corrugated asbestos paper separators stiffened by a water glass treatment, a perforated steel frame, and a refractory furnace cement for sealing the filter pack to the steel frame. The filter was completely fire-resistant, but it was heavy and the refractory furnace cement adhesive embrittled the filter paper, produced air leaks, and imparted a distressing tendency for the filter pack to separate from the steel frame. This filter assembly became obsolete after the introduction of high chlorine- or bromine-content, self-extinguishing, flexible organic adhesives and the development by A.D. Little Company of a fiber blanket seal that was compressed between the filter pack and metal frame.

Hurlbut Paper Company and Hollingsworth and Vose Company produced an air filter paper in the mid-1950s that was made from Carborundum Corporation's Fiberfrax fibers. These fibers were comprised of silicon oxide-aluminum hydroxide and could withstand temperatures up to 2,000 degrees Fahrenheit for long periods and in excess of 3,000 degrees Fahrenheit for shorter periods. With this paper, plus loose Fiberfrax fibers of various grades, Flanders Filters, Inc., was able to fabricate an all-ceramic filter (i.e., Fiberfrax paper, separators, filter-frame, and sealant) that was capable of performing satisfactorily at temperatures in excess of 2,000 degrees Fahrenheit and had extraordinary resistance to heat shock.[15] However, it proved impossible to produce Fiberfrax fibers fine enough to provide filter efficiencies equal to those available with all-glass-fiber papers, and interest in Fiberfrax filters waned.

### 1.1.4 Commercial Development

After development of the absolute filter by A.D. Little, a manufacturing capability was installed at the Army Chemical Center at Edgewood, Maryland, and Little also started the first commercial manufacturing company, Cambridge Filter Company. Little shortly sold Cambridge after a decision to restrict their efforts to research.

By 1957, three firms were fabricating absolute filters. Following allegations that defective filters were being delivered to AEC facilities, the AEC requested that sample filters representing procurement from each of the three filter manufacturers be removed from AEC facility stocks and sent to Edgewood, Maryland, for inspection and test. Seven of the 12 filters received by Edgewood were obviously defective after removal from their shipping cartons. Testing was unneeded for this determination.[16] AEC facilities were advised to open and inspect the filters held in their stocks, and facility responses indicated a similar proportion of defects.

Based on these findings, the AEC initiated quality assurance (QA) inspection and testing of filter deliveries for each half of the continent, installation of a test facility at Richland, Washington, and an agreement for QA testing by Edgewood for the eastern half of the United States. Oak Ridge, Tennessee, replaced Edgewood following installation of testing equipment in 1964. A QA facility was activated at the Rocky Flats Plant in Golden, Colorado, in 1970. Currently, both the Rocky Flats and Richland facilities are demobilized.

In the same time frame, a Government-Industry Filter Committee was established with voluntary participation that included representatives from filter manufacturers, filter medium makers, the sole supplier of glass fibers, users, and government agencies and organizations, including the Army Chemical Center and the NRL. Discussion sessions were held before the biennial AEC Air Cleaning Conferences, and working sessions were convened at Underwriters Laboratories (UL) in Chicago, Illinois. Topics ranged from the aging of glass fibers to the integrity of shipping cartons. The committee provided guidance to the Army Chemical Center concerning military standards for fire-resistant filters and its glass fiber filter medium, and also advised UL in establishing their UL-586 standard for filter heat resistance. The committee was responsible for considerable technology exchange in view of the relative newness of the glass fiber filter medium and the undeveloped technology for its fabrication into filters.

### 1.1.5 Development of HEPA Filter Standards

With the Army's issue of MIL-F-51068[46] for the fire-resistant filter and MIL-F-51079[42] for the glass fiber medium, Edgewood abandoned its manufacture of the cellulose-asbestos filter and turned to commercial procurement. These standards documents have remained in service almost to the present. In 1994, due to changing requirements, the availability of new materials, improved instrumentation, advanced technology, and a U.S. Department of Defense emphasis on consensus standards, the U.S. Army announced it would no longer maintain MIL-F-51068[46] and MIL-F-51079[42] in active status. Maintenance of these standards was taken over by the American Society of Mechanical Engineers (ASME)-sponsored nuclear code-writing Committee on Nuclear Air and Gas Treatment (CONAGT). Improvements were incorporated into the standards with the concurrence of the other military services and the U.S. Nuclear Regulatory Commission (USNRC).

The HEPA filter design used by the United States nuclear industry is very nearly identical to the one used in the United Kingdom and has been the mainstay of the nuclear industry for the past five decades. Additional progress was made in the documentation and codification of standards for filter installation and testing with the issuance by the American National Standards Institute of ASME N509, "Nuclear Power Plant Air Cleaning Units and Components"[2] and ASME N510, "Testing of Nuclear Air Cleaning Systems."[1] Although these two standards were intended to apply only to the construction and testing of engineered safety systems in U.S. civilian nuclear power plants, the major part of each standard can be and often has been applied with salutary results to air cleaning systems in all manner of nuclear facilities in the United States and abroad. CONAGT has transferred many sections of ASME N509 and N510 into ASME AG-1, "Code on Nuclear Air and Gas Treatment."[3] The contents of the early editions of these two standards were substantially incorporated into USNRC Regulatory Guide 1.52, Revision 1.[29] Some standard-setting agencies in other countries with a significant nuclear power establishment have prepared and issued similar standards that differ only in details. The principal modification to the military standards since 1968 centers around requirements for the resistance of the filter medium to radiation (prolonged filter effectiveness following a core-disruptive accident). For ease in procurement, the military service (Edgewood Arsenal) qualified a number of producers' HEPA filter paper and assembled filters and published their names in a Qualified Products List (QPL).[9]

### 1.1.6 FURTHER DEVELOPMENT OF THE HEPA FILTER

Thin, aluminum-alloy, corrugated separators completely replaced asbestos, thermoplastics, and resin-treated Kraft paper to assure fire-resistance. Stainless steel is often selected because of its resistance to severe chemical attack, but aluminum-coated plastic is satisfactory for less corrosive service. Improved resistance to wetting, an issue of major importance for engineered safety system filters in water-cooled reactors, was developed by applying water-repellent chemicals to the filter paper. For such applications, it has become standard practice to install the filters with the paper folds in the vertical position so that any water droplets captured on the surface of the paper will drain to the bottom of the filter.

### 1.1.7 INTRODUCTION OF HEPA FILTERS FOR TREATING REACTOR EFFICIENT GASES

The first nuclear reactor fitted with effluent high-efficiency air filters is believed to have been the graphite-moderated, air-cooled unit at Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee. The initiating event was the discovery in 1948 of radioactive particles up to 600 μm in size on the ground around the reactor stack. A reinforced concrete filter house capable of handling 240,000 $m^3$/hr of air at a temperature of 102 degrees Celsius and a negative pressure of 12.5 kPa was constructed to prevent further emissions.[28] This was also one of the first installations to use prefilters to extend the life of absolute filters as a means of reducing air cleaning costs. The filtration system contained 2.5-cm-deep resin-bonded fiberglass prefilters that removed the coarsest dust fraction, followed by 61- x 61- x 30-cm Army Chemical Corps cellulose-asbestos units (later designated AEC no.1) in plywood frames. Design efficiency was 99.9 percent for particles down to 0.1 μm. The high-efficiency filters were changed when airflow resistance was increased from 0.25 kPa to 1.25 kPa over a period of about two and a half years. It was found that the service life of the absolute filters could be extended to more than two years by changing the prefilters two to three times per year. Although there have been situations where a cost analysis failed to show an advantage from using prefilters, most installations seem to benefit from using cheaper prefilters. There is continuing interest in the use of metal prefilters because, in addition to coarse particle filtration, they provide fire and blast protection by acting as baffles and fire screens.

### 1.1.8 HEPA Filter Quality Assurance

During the 1960s, major efforts in the United States were directed toward standardizing manufacturing and test criteria for paper and fabricated filters, with special emphasis on fire and water resistance. Manufacturer testing of each individual filter for collection efficiency and airflow resistance had always been a unique requirement for filters intended for use in nuclear service. The results of each test are noted on the filter frame to assure that the filter meets the requirements of applicable standards. Initially, the efficiency standard for 0.3-μm test aerosols was 99.95 percent, but it was raised to 99.97 percent after commercial filter manufacturers found ways of improving their materials and assembly techniques to a degree that enabled them to turn out filters exceeding the required particle retention efficiency by more than an order of magnitude. These new filters also featured improved resistance to corrosive chemicals, fire, and radiation.

Similar filter efficiency standards were developed in Great Britain (using a nebulized salt aerosol) (BSI, 1965),[7] France (using a nebulized uranine aerosol),[4] and Germany (using a paraffin oil aerosol).[15] Because of differences in measuring filter efficiencies, considerable effort has been expended (with indifferent success) on laboratory studies to develop conversion factors that would translate the filter efficiency measurements made by one method to equivalent values derived using a different measurement method.[13] It would be convenient if everyone used the same filter test method, but this is unlikely in the foreseeable future.

The wide diversity of aerosols generated in nuclear industries raises an important question regarding the relevance of the qualification test procedures utilized. For example, the aerosols predicted to be present inside the containment vessel of a power reactor following a loss-of-coolant accident (LOCA) are certain to be very different from the test aerosols and efficiencies observed during the standardized qualification tests and are not necessarily the results that will be obtained in practice. They may be better or worse depending on the characteristics of the aerosol challenge. However, passing a standardized qualification test gives reasonable assurance that the filters have been produced from high-quality components and carefully assembled to exacting standards. Therefore, the standard qualification test results should be viewed as an index of merit (an indication of quality) rather than a quantitative description of filter efficiency under unknown or ill-defined operating conditions.

Nevertheless, about 1990 the U.S. Department of Energy (DOE) undertook a program designed to define HEPA filter efficiency more precisely with the aid of an intercavity laser particle size spectrometer capable of counting and sizing aerosol particles down to approximately 0.08 μm under careful laboratory manipulation.[27] The impetus for this program was the discovery that the monodisperse 0.3-μm test aerosol, when defined using methods developed during the 1940s, was neither monodisperse nor always 0.3 μm.[19] Filter efficiency studies conducted at Los Alamos National Laboratory produced the following results.

- The most penetrating particle size for all-glass-paper HEPA filters operated at the design airflow rate is close to 0.1 μm.
- A new HEPA filter acceptance standard was developed that used a polydisperse aerosol, but this method counted only 0.1-μm particles upstream and downstream of the filter to rate particle retention efficiency.[10]
- Programs were conducted at DOE's Filter Test Stations to improve the characteristics of the aerosol used for routine filter testing (e.g., making the test aerosol more uniform in size and closer to an average size of 0.3 μm).

To a significant degree, the establishment of AEC QA Filter Test Stations in 1960 made it imperative for filter manufacturers to institute their own rigid quality control practices to avoid product rejection at the filter test stations. For example, 49 percent of filters manufactured prior to 1960 were rejected at the filter test stations, whereas only 5 percent were rejected during the following eight years.[8] By 1978, the rejection rate had declined to a point where the USNRC was willing to forego QA Filter Test Station inspection of filters intended for use in engineered safety feature (ESF) systems in commercial nuclear power plants on the basis that the marginal increase in the reliability of tested filters no longer justified the additional cost.[8] Considering the large number of specifications, requirements, and standards that have been proposed and adopted for HEPA filters, it is clear that they are among the most extensively and thoroughly documented devices in the entire air filtration spectrum.

### 1.1.9 HEPA Filter Application Assurance

In spite of the many improvements in absolute [HEPA] filters, it was discovered as early as the initial installation of HEPA filters at the ORNL graphite reactor that the full capabilities of improved filter performance were not always achieved because of damage during shipment and faulty installation. Consequently, it has become routine to conduct in-place testing of all filter installations using methods initiated and developed at ORNL prior to startup of new facilities and periodically thereafter. A great deal has been learned about the correct design of filter housings and filter installation methods from in-place testing. For example, considerable difficulty was experienced in conducting tests at old installations because easy access to the filter structures was not provided. It became clear that suitable facilities for in-place filter testing must be designed into all new systems as part of the construction specifications. The value and effectiveness of correctly designed and installed nuclear-grade aerosol filtration systems are illustrated by the very different events that took place at the Three Mile Island-2 (TMI-2) and Chornobyl reactors. During the March 1979 LOCA at TMI-2, two 51,000 $m^3$/hr filter systems prevented essentially all of the particulate material and the bulk of the radioiodine from being released to the environment.[5] Consequently, release of radioactive particles to the environment was negligible. During the April 1986 fire at Chornobyl Unit 4, however, where engineered safeguards did not include complete containment with air filtration systems, the outcome was very different. The widespread apprehension engendered by that accident is likely to result in a demand for still higher collection efficiency and greater filter resistance to internal disruptive events (fires, explosions) and to external natural disasters such as earthquakes and tornadoes. The response to this need in Germany[11] and the United States[6] has been the development of filters composed of stainless steel fibers.

### 1.1.10 Increasing Air Flow Capacity of HEPA Filters

Although British filter construction methods and filter materials closely paralleled American ones, manufacturers in other European countries developed a different HEPA filter design that is now made by some U.S. manufacturers. Instead of filter paper pleats that extend the full depth of the filter frame, the paper is folded into mini-pleats about 20-mm deep with a pitch of 3 mm. Adjacent pleats are separated by ribbons or threads of glass, foam, or plastic. A full-size filter is assembled from several component panels of this construction and arranged around a series of V-shaped air passages. This design allows considerably more filter paper to be incorporated into a given volume, making it possible to replace a standard 61- x 61- x 30-cm U.S. filter unit with one of identical dimensions that can handle up to 0.9 $m^3$/sec instead of 0.5 $m^3$/sec at a clean filter resistance of 0.25 kPa and that can meet the maximum test aerosol penetration standard of 0.03 percent at the higher volumetric flow rate.

A different filter that does not use separators has been fabricated by a U.S. manufacturer. The corrugations are made by vacuum-molding the wet filter paper onto narrow longitudinal ridges while it is still on the paper-making machine, then accordion-pleating the paper as it comes off the machine.[13] The preformed corrugations are impressed into the paper at a slight angle to the run of the sheet so that, when folded, the pleats in alternate layers resist nesting. A later development of this process is to impress dimples into the forming paper so that, when folded, the dimples prevent alternate paper layers from touching each other. This filter construction method is different from the one used for the older mini-pleat filters in that the filter pack is mounted into the filter frame in the usual way (i.e., perpendicular to the air flow direction) rather than as a number of 20-mm-deep panels arranged inside the filter frame in a series of V-formations. A 6-in.-deep mini-pleat separatorless filter contains the same area of filter paper as the 12-in.-deep separator type. This filter has been placed into service, but there is no experience to report concerning nuclear applications.

### 1.1.11 DISPOSAL OF SPENT FILTERS

It often costs more to dispose of a contaminated spent filter than its initial purchase price, which reflects the difficulties associated with handling contaminated wastes and the shrinking number of authorized disposal sites. During the early years of the nuclear age (when HEPA filters were constructed with wooden frames, corrugated separators, heavy Kraft paper, cellulose-containing filter paper, and conventional rubber cement) high-temperature incineration resulted in a 99 percent reduction in bulk. This was considered at the time to be the best way to handle used filters, and a number of incinerators were constructed and used to reduce the bulk of all combustible contaminated wastes, including spent filters. However, the incinerators quickly became contaminated and proved difficult to operate and repair in a safe manner. To protect the environment, HEPA filters were installed as the final flue gas cleaning element, but they proved to have a short service life in incinerator service. Processing the spent flue gas filters through the same incinerator they were installed to serve greatly increased the burden on the incinerator, thereby reducing productive throughput and elevating costs.

During the 1960s, as a result of the introduction of noncombustible elements into the structure of HEPA filters intended for nuclear service and the introduction of heavy presses designed to crush HEPA filters into a small volume for ground burial at little cost, outmoded high-temperature volume reduction incinerators were shut down and dismantled. Where recovery of transuranic elements from spent filters remained a requirement, devices were developed to extract only the filter paper from the frame for chemical or high-temperature treatment. The remainder of the filter was disposed of by crushing and burial.

The rapidly escalating cost of land disposal for radioactive wastes, in addition to new requirements for corrosion- and leak-proof containers that substantially increase the bulk of the waste package, have combined to renew interest in the volume reduction of wood frame filters by high-temperature incineration in spite of an obvious incompatibility between a need for noncombustible filters and a wish to minimize disposal costs by high-temperature volume reduction. Exclusive use of separatorless HEPA filters helps reduce the residue from incineration. When using metal frames and corrugated aluminum separators, alternatives include punching out the filter pack into a high-pressure press for volume reduction and decontaminating the metal parts via chemical treatment. Incineration of contaminated HEPA filters continues to present formidable operating difficulties and high costs. Additional difficulties are experienced when the substances collected on filters are classified as both hazardous chemical and radioactive wastes.

## 1.2 DEEP-BED SAND AND GLASS FIBER FILTERS

Although HEPA filters came to dominate aerosol containment for most nuclear applications, from the beginning there were other filter innovations of note. When a high-activity level was detected at Hanford, Washington, in 1948 and traced to radioactive particles emitted from the chemical processing ventilation stacks, the chemical engineering practice of using deep beds of graded granular coke to collect mists escaping from contact sulfuric acid plants was recalled, and a number of large sand filters were constructed during the late 1940s and early 1950s at both the Hanford and Savannah River Sites.[23] The sand filters closely followed the deep-bed (100- to 300-cm-deep) graded-granule techniques for building granular filters that were widely accepted at sulfuric acid manufacturing plants and for the purification of municipal drinking water supplies. These filters had collection efficiencies for particles greater than 0.5 μm that compared favorably with the best fibrous filters then